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Techno-Economic Analysis of Single-Pass Maize Biomass Harvest Systems

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Techno-economic analysis of single-pass maize biomass harvest systems

by

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Abstract

This study was focused on the economic impact of corn residue harvest systems on typical grain harvesting. In Chapter 2, the single-pass stover harvest system with several equipment application logistics is examined; in Chapter 3, both existing and potential single-pass cob harvest systems were evaluated with respect to harvest work time length, equipment and labor requirements, harvest cost, and post-harvest costs related to residue collection. Residue collection actually increased harvest time due to the lower harvest rate caused by additional material passing through the combine. Field traffic increased as additional equipment is required during harvesting; an increased labor requirement was also an important result in all harvest scenarios. In the stover single-pass harvest scenario, increasing on-board stover density helped to significantly reduce equipment and labor requirements. Nutrient replacement and long-term field side storage needs related to the residue harvest also contributed to harvest cost and could not be neglected.

CHAPTER 1

General Introduction

As economy and technology are advancing, whether the energy supply will be able to meet requirements while maintaining long-term sustainability has become an important issue. Enhancing fuel-utilizing efficiency and developing sustainable energy resources are the main focuses of EISA 2007.

In the early 20th century in the US, ethanol first became an alternative fuel, and later a fuel additive, especially after the prohibition of MTBE. The ethanol industry has been under federal support since the 1970s (Solomon et al., 2007). However, up to the present time, the major commercialized form of ethanol in the US is still starch ethanol. Since grain from which this starch is obtained can also have the ability to serve as a food source, a concern has been raised that, even with growing yields, starch ethanol growth might face a future limitation due to balancing between fuel and food needs, and will not able to satisfy energy goals. On the other hand, cellulosic feedstock, developed as ethanol source, is an alternative for the next generation because of its lower life-cycle energy consumption relative to starch ethanol and gasoline (Farrell, 2006). However, use of third-generation cellulosic feedstock is still in a research phase and not yet available on a commercial scale; in the near term, second-generation ethanol, produced from agricultural and forest residues, is the leading competitor to starch ethanol (ERDB, 2008).

In the United States, corn is a principal agricultural product; corn stover, the residue remaining after grain harvest, is estimated to be able to provide at least 68M Mg per year.

With technology advancement and agricultural land expansion, this yield is estimated to grow to over 320M Mg per year (Perlack, 2005).

Corn stover has been harvested for a long time on a smaller scale as animal feed and bedding material; it is harvested by traditional methods and usually stored in the field. Harvesting stover requires additional labor work and time, and usually requires custom work (Hettenhaus et al., 2000). During 1997-1998, a large-scale collection was conducted in Iowa, to demonstrate the possibility of collecting stover for ethanol within a reasonable working time and for estimating the cost of custom harvesting at about \$34.76 to \$39.30/dry Mg, depending on amount of residues removed (Glassner, 1998).

As previously mentioned, traditional stover collection requires several custom tasks, including shredding, raking, and baling. This traditional system also requires working with dry stover, in spite of the fact that drying conditions in the corn belt may be unable to meet the harvest demand. Previous research has shown wet stover may be stored with low dry matter loss over a long interval, so it may be possible to harvest wet stover and combining the required custom tasks with grain harvesting. In a single-pass system, the combine is modified to complete the chopping and blowing work while harvesting, and chopped stalks are directly collected (Shinners et al., 2007a; Shinners et al., 2007b). There are different methods for collecting stover, e.g., directly collecting in carts or baling with a pull-type baler associated with the combine.

However, damage to soil in uncovered fields is still controversial; removing stalks from the field after harvesting is reported to reduce tillage work in the next crop cycle and reducing the harvest cost and soil work, but reports have also shown that in some corn belt locations (Iowa for example), removing crop residue from the surface induces soil and nutrient loss, further decreasing soil fertility (Hettenhaus, 2000). The “harmless” percentage that can be removed while maintaining sustainability depends on soil conditions and terrain at each site. There are studies suggesting that the recommended surface residue removal percentage might vary between 35% and 75% depending on site condition (Lindwall et al., 1996). Facing this soil loss problem suggests that removing only the cob portion might become a reasonable choice.

Cobs are much denser and contain more energy than stalks. They are presently being collected as a material for minor industrial use, but are not used as feedstock for fuel. Thus there are some existing cob collection technologies, such as collection in the mixed material stream along with grain (Corn Cob Mix) or by cob caddies (Davidson, 2008). Collecting mixed cobs requires further separation; single-pass spilt-stream stover harvesters, with adjustment for the cobs, are able to eliminate the separation task.

The issue induced by stover collection is not just the harvest; harvest cost also includes cost to replace removed nutrients and storage cost if the stalk is going to long-term storage as a commercial feedstock. Stover silage following the traditional method of hay silage been widely studied (Buxton ed., 2003); there is less information about cob storage. One study in 1985 reported that cobs could be stored in piles on the field, with dry matter loss between 13.8% and 20.2%, but it was possible to lose 33% of their energy content, requiring further studies on cob storage (Smith et al., 1985).

Since the residue harvest work affects typical grain harvest pattern, equipment, and time, its effect on typical grain harvest work during the harvest season becomes important. In this study, models simulating field logistics with corresponding field properties were applied to estimate timely change and required additional harvest tasks, followed by evaluating residue harvest cost, labor, and equipment requirements, and finally providing an evaluation of the impact from residue harvest work.

Thesis Organization

This thesis follows the journal article format and includes two papers to be submitted to refereed journals, each presenting a part of an overall analysis of corn-residue harvest cost analysis. The first paper, which is Chapter 2, presents the results of single-pass stover harvest cost analysis modeling, and the second paper in Chapter 3 presents the results from several current and developing cob harvest systems; the detailed description of the model applied is presented in Appendix A. The general issues related to residue harvesting and overall results of these studies are discussed in the General Conclusions, Chapter 4.

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CHAPTER 2

Cost Analysis of Single-pass Corn Stover Harvest Systems

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A paper to be submitted to *Biomass and Bioenergy*

Abstract

Single-pass corn grain and stover harvesting is seen as an opportunity to maintain quality and reduce cost of stover collection. This study evaluates single-pass stover harvesting cost based on a set of experimental combine experiments. A spreadsheet-based optimization model was developed to determine the lowest possible total harvest cost, nutrient replacement cost, and field-side storage cost under three machinery strategies and various stover collection rates. It is assumed that corn is the only crop, base grain yield is 9.41 Mg/ha, and the stover harvest density is 48.06 kg/m^3. Model analysis indicates that at a yield of 9.41 Mg/ha, the lowest stover collection cost is $25.30/dry Mg at a 75% stover collection rate. When the grain yield is 12.55 Mg/ha, stover collection cost rises to $29.11/dry Mg, due to harvest time increasing by 24%. Increasing stover harvest density helps to reduce harvest cost and is an important variable in one design. Nutrient replacement cost and storage cost play important roles and each can be as much as 30% of total edge-of-

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[1] Corresponding author; designed study; reviewed model; reviewed and edited paper
[2] Provided equipment performance data; reviewed and commented on paper
[3] Provided equipment performance data; reviewed harvest system simulation results
[4] Provided stover storage data; modified stover storage model

field stover cost. For the different designs evaluated, the total cost of collection, storage and nutrient replacement at 9.41 Mg/ha is between $63.27/dry Mg and $119.04/dry Mg.

Introduction

Energy consumption is a main concern related to rapid economic and technology advances, mainly based on non-renewable fossil fuels; in the United States, the problem further involves energy independence, since this country relies heavily on imported oil. Producing renewable energy within the states has thus become a high-priority task.

The extensive agricultural industry in the US supports biofuel production. Currently, first generation biofuels, such as corn ethanol, are already on the market. However, these feedstock-based fuels are controversial because of their use of food and feed sources; new energy crops, capable of conversion into fuel with lower energy consumption [1], are in demand but are also still in development. Agricultural residues have become candidates for near-term adoption because the supply source is already ensured [2].

As an agricultural residue, corn stover has the potential to satisfy ethanol need on a large scale [3]. However, one of the important issues in cellulosic ethanol production is the feedstock price that mainly accounts for ethanol cost [4]. Studies based on traditional harvesting methods have been presented, and a study in 2003 summarized typical stover collection cost, which was likely to lie between $21.60/dry Mg and $23.60/dry Mg [5].

Traditional harvest methods require additional custom work; engineers are working on combining harvest steps to simplify the harvest work. Single-pass harvest systems were thus developed and tested [6]. A new single-pass system capable of direct delivery of chopped stalks into hauling equipment and finishing both grain and stover collection work at the same time has been developed [7].

An Iowa State University team developed the dual-stream harvest system, with grain and stover streams separated, allowing the stover to be hauled with typical forage carts. From an economic aspect, this study established a model with typical assumptions, and used it in evaluating system characteristics, including time consumption, equipment and labor requirement, and stover harvest cost, as well as related cost that also play a part in feedstock price.

Material and Methods

This study will be evaluated in three parts: The main part is the harvest model established to evaluate harvesting cost with specific equipment use; the second part determines the post-harvest cost induced by stover collection, and the last part compares this methodology with traditional custom work.

A. Harvesting model

A biomass harvesting spreadsheet model was implemented to estimate the harvest cost. It included three main sections: (a) combine harvesting section, (b) tender utilizing section and (c) harvest budget section.

Combine harvesting section

This section estimates the combine harvest speed by yield and system design, and also estimates average material flow rate as well as total harvesting time. During harvesting, the average combine speed was an constant and able to be derived from an experimental function of yield.

Theoretical combine speed (m/min) = $(\text{-}0.01 \times \text{yield in bushel} + 5.37) \times 26.82$

Actual combine speed (m/min) = Theoretical combine speed × speed reduction

In the model, there were two biomass streams, the grain stream and the stover stream, emerging from the combine. . The material flow rate of chopped stover stream depended on the grain flow rate and the harvest index.

Tender utilizing section

The tenders used in this model refer to one of three combinations: (1) One tractor pulling one grain cart ("grain tenders"), (2) one tractor pulling one or two stover carts ("stover tenders"), or (3) one tractor pulling one grain cart and one stover cart ("combined tenders").

Three strategies were applied with respect to tender utilization. These were defined as scenarios in later sections. The three scenarios included:

Scenario 1: Independent grain and stover tenders, with single stover outflow

Grain tenders and stover tenders were applied in this scenario. A stover tender followed the combine until its cart was full, and then directly left the combine. While the next tender was catching up, the stover was left on the ground. Tender speed was a constant, thus, in order to capture more stover, more stover tenders would be required.

Scenario 2: Independent grain and stover tenders, with two stover outflows

This scenario was similar to the first one; however the percentage of stover captured was determined at the combine side. The stover stream was divided by a designed ratio, one the main stream to collect, and the other one the disposal stream distributing all the stover along. This required one stover tender following the combine at all times in order to capture all materials from the main stream. This scenario left the uncollected stover distributed evenly over the field.

Scenario 3: Combined tenders, with a single stover stream

This scenario was similar to the first one; however combined tenders instead of independent grain and stover tenders were used. Grain and stover were filled into carts at the same time while the combined tender follows the combine harvester; the stover was left on the ground once the tender left or when the stover cart was full, but the grain cart was still being filled. In order to capture more stover, more combined tenders were required, and the grain-filling period was shortened.

In this tender utilizing section, the minimum tender requirement with the ability to capture an assigned percentage of stover was determined by the model.

Harvest budget section

With detailed equipment usage and harvesting time, the total harvest cost, including both capital cost and operation cost, based on formulas from Iowa State Extension Document PM710 [8] and ASABE standard document D497.5 [9], were determined. The cost was mainly a function of harvesting time. One important change was increased fuel use, resulting mainly from additional power requirement:

Extra power requirement (kw)=

*(1.65 * Biomass feeding rate (Mg/hr) +17.13)*

This formula was based on experimental field results. The total power requirement was the original power plus extra power requirement. The cost to harvest stover was then defined as:

Total cost (with stover harvesting) – Total cost (grain harvesting only)

Besides evaluating the basic stover harvest cost, different sets of field parameters were applied to test the importance of field characteristics.

The main assumptions used in the model above are listed in Table 1.

B. Related post-harvest cost

Following the harvest cost, storage and nutrient replacement cost were also evaluated.

Nutrient Replacement Cost

It was assumed that extra nutrients would be applied to the field at the next farming period in order to replace the nutrient removed with the stover. This part presented the cost of additional required fertilizers. The nutrients removed with the stover were taken from average nutrient contents presented in previous study results [7]. The fertilizer prices used to calculate replacement cost are also presented in Table 1.

Storage cost

Two storage methods, covered piles and plastic bags, were considered here by applying Holmes's storage spreadsheet model with essential scaling factors [10] [11]. In this evaluation, it was assumed that corn was the only crop in the field.

Well-packed stover was stored for 365 days and assumed to be further transported to a biorefinery at about the same time. The storage cost evaluation included building or packing materials, machines, implements, and labor costs incurred in establishing piles and bags, as well as the lost value due to dry matter loss.

Table 1. Common harvesting constants

Category	Item	Value
Combine	List Price ($[5])	200,000
	Power (kW)	242.35 (325 HP)
	Bin Capacity (m^3)	10.6
	Bin Unloading Rate (m^3/min)	5.5
	Speed Reduction with Stover Harvesting	25%
	Modification Cost ($)	50,000
Corn head	List price ($)	30,000
	Head Width (m)	9.1
Tractor & Trailer Set	List price - Tractor ($)	75,000
	Tractor Power (kW)	78.29 (105 HP)
	Field Speed (m/min)	268.2
	Large Grain Cart	
	Capacity (m^3)	30.3
	Price ($)	27,000
	Small Grain Cart	
	Capacity (m^3)	24.2
	Price ($)	27,000
	Stover Cart	
	Capacity (m^3)	43.0
	Price ($)	35,000
	Assumed unloading rate (m^3/min)	15
Field	Total Area (ha)	809.37 (2000 acre)
	Field Unit (ha)	64.74 (160 acre)
Economics	Real Interest Rate	8.0%
	Wage Rate ($/hr)	15
	Hired Labor	100%
	Diesel Price ($/liter)	1.06 ($4/gal)
Biomass	Harvest Index	0.52
	Stover bulk density (kg/m^3)	48.06
	Grain Price ($/Mg)	196.8
	Stover Price ($/dry Mg)	100

[5] In 2006 dollars

Table 1 (continued). Common harvesting constants

Category	Item	Value
Fertilizer	Nitrogen Price ($/kg)	1.10 ($0.5/lb)
	Phosphate Price ($/kg)	1.76 ($0.8/lb)
	Potash Price ($/kg)	0.88 ($0.4/lb)

C. Comparison with traditional multi-pass systems

To permit comparison with traditional harvest methods, the cost of a traditional multi-pass system was calculated using typical Iowa custom work rates from Iowa State Extension documents. Two harvest methods were evaluated: round bales and large square bales. Stover properties were the same as assumed in previous evaluations. Other assumptions are listed in the Table 3. Calculations are in table 3 and 4.

Table 2. Multi-pass system assumptions

Item	Round bale system	Square bale system
Stover recovery rate[6]	49%	46%
Bale DM weight [7]	0.58 Mg/bale	0.77 Mg/bale

Table 3. Round bale system

Stage	Custom Rate	Source	Stage Cost ($/ha)
Shredding	19.77/ha	Iowa State custom stalk chopping rate [12]	19.76
Stover baling	10.10/bale	Iowa State custom RD/SQ baling rate	44.58
Moving bales to the edge of the field	2.25/bale	Iowa State rate of moving RD bales	9.93
Total			$70.28/ha
Per DMg cost			$29.17/Mg

[6] [5]
[7] [5]

Table 4. Large square bale system

Stage	Custom Rate	Source	Stage Cost ($/ac)
Shredding	19.76/ha	Iowa State custom stalk chopping rate	19.76
Raking	12.10/ha	Iowa State custom raking rate	12.10
Stover baling	10.10/bale	Iowa State custom RD/SQ baling rate	31.30
Moving bales to the edge of the field	2.25/bale	Iowa State rate of moving RD bales	6.97
Total			$70.18/ha
Per DMg cost			$29.35/Mg

Results and Discussion

A. Harvest Cost

Harvest costs were estimated from the model. The lowest per Mg cost was $25.30/dry Mg, estimated for scenario 1 and scenario 2. Costs were between $25.30/Mg and $64.57/Mg; differences resulted mainly from the amount of harvested mass, since the work can be done with similar sets of equipment.

However, besides harvesting costs, some combining effects were found in the results. The first effect was longer harvest time; the combine speed was reduced due to collecting extra biomass instead of grains. Comparing with the grain-only case, harvesting time was about 24% longer.

Additionally, traffic in the field was also increased. With stover harvesting, at least one more tractor ran in the field during the whole harvesting period; in order to collect 75% of stover, two more tractors were required in all scenarios. This might also induce additional soil compaction to the field.

The calculation results are presented in Table 5.

Table 5. Results from three original scenarios (when grain yield was 9.41 Mg/ha)

Scenario	Collection %	Tenders required[8]	Total labor hours	Harvesting time (hr)	Harvest cost ($/Mg)	Grain cart filled %
Scenario 1	25%	2 (1+1)	778.80	259.6	42.06	100%
(Separated	50%	3 (1+2)	1038.40	259.6	32.29	100%
systems /Spillage)	75%	3 (1+2)	1038.40	259.6	25.30	100%
Scenario 2	25%	3 (1+2)	1038.40	259.6	64.57	100%
(Separated	50%	3 (1+2)	1038.40	259.6	37.95	100%
systems /2 streams)	75%	3 (1+2)	1038.40	259.6	25.30	100%
Scenario 3	25%	2	778.80	259.6	52.09	30%
(Combined	50%	3	1038.40	259.6	39.49	15%
system /Spillage)	75%	3	1038.40	259.6	26.32	12%
Grain-only	N/A	1	418.03	209.0	0	100%

Compare with traditional system

From Table 3 and Table 4 in the previous section, the traditional method costs with a 2006 Iowa custom rate were around $29/Mg. However, the estimated stover collection recovery ratio was no more than 50% in both cases; thus, compared with the harvest cost from previous results at 50% collection level, the single-pass system could be 33% higher.

Elements affecting harvesting cost

(a) Total harvesting time

The harvest time directly affected harvest cost; thus variables associated with time would contribute to a cost difference. Yield was another important factor, since it controlled the

[8] Numbers in the column of “tenders used” include both grain tender and stover tender (if in separated systems). For example, “2 (1+1)” represents one grain tender and one stover tender required, and two in total.

general harvest speed. The comparison of harvest cost at grain yield was 9.41 Mg/ha and 12.56 Mg/ha is presented in Figure 1 below.

Although the yield increased one third, the difference was not directly proportional. It was due to the combine harvest rate: the harvest speed decreased as the yield increased, thus the grain mass flow rate only increased 1.1%. However, since the stover density is low (48.06 kg/m^3), the increased volume of stover was relatively large. At lower collection level (25%, 50%), there was unused capacity that was enough to complete the harvest work with the same amount of equipment, thus the per Mg cost is lower; however, at a 75% collection level, more equipment was required at grain yield of 12.56 Mg/ha, thus the cost increased 12%-15%.

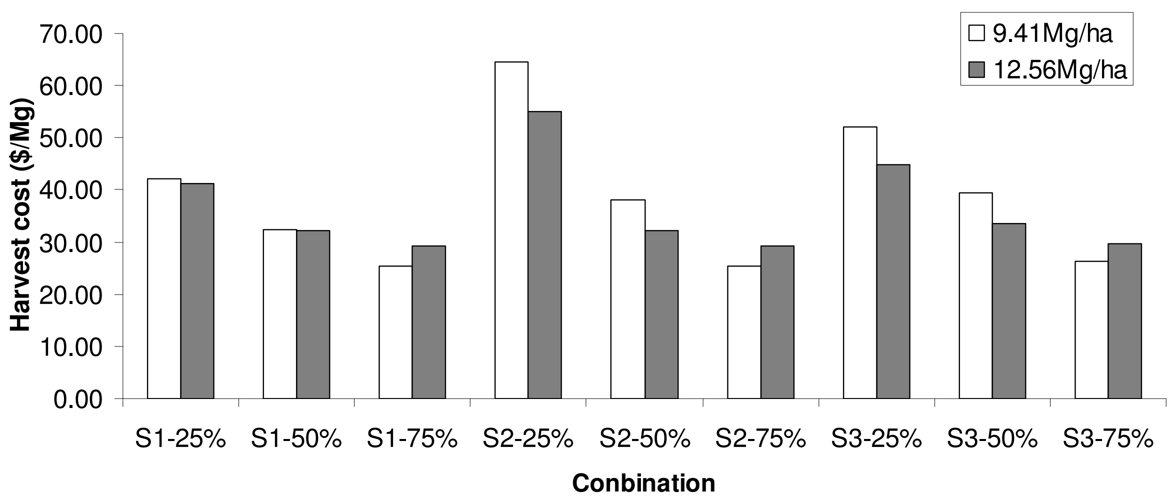

Figure 1. Changes due to increasing yield; per Mg cost was higher at 75% collection level due to higher equipment requirement

(b) Equipment use

At a certain harvest speed and a certain harvest time interval, the other cost-affecting factors would then result from the stover collection activity and from the equipment requirement. By increasing on-board density, the space required for stover storage was decreased, and the collection work could be done with fewer tenders or stover carts. Thus, the cost was lowered by as much as about 30% in the third scenario. The second scenario design required two tractors following the combine at all times and thus it wasn't benefit from increasing density at a low collection level. The situation in the third scenario was similar, since stover will be lost during a grain-loading period and wouldn't benefit much at a lower collection level.

With a higher on-board density and lower equipment use, unit cost would be lower than present custom harvest cost.

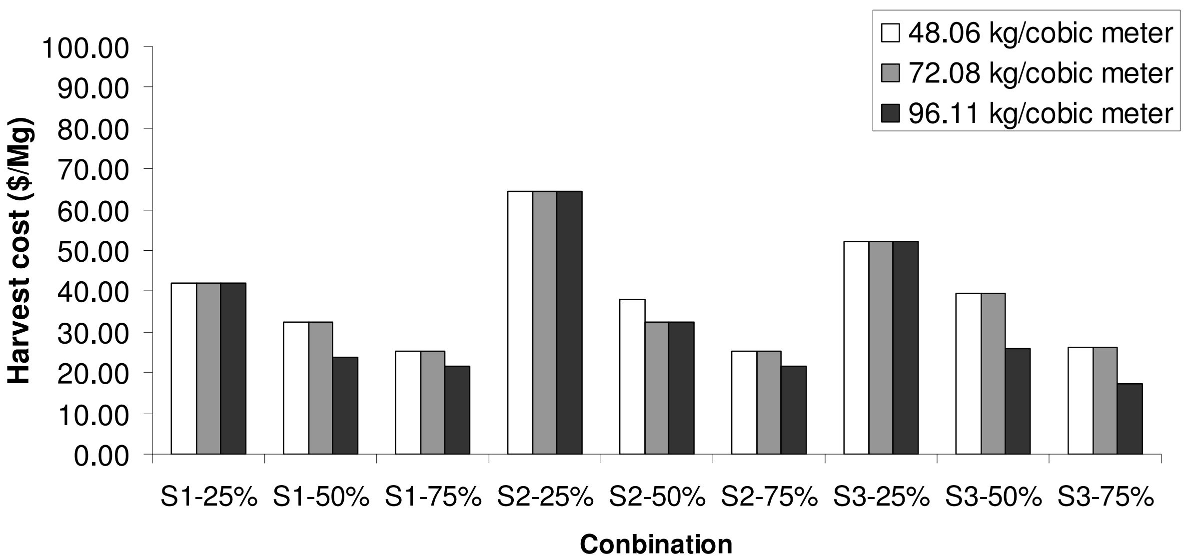

Figure 2. Effect from increasing density at 9.41 Mg/ha; per Mg cost was decreased at higher density because of fewer equipment used

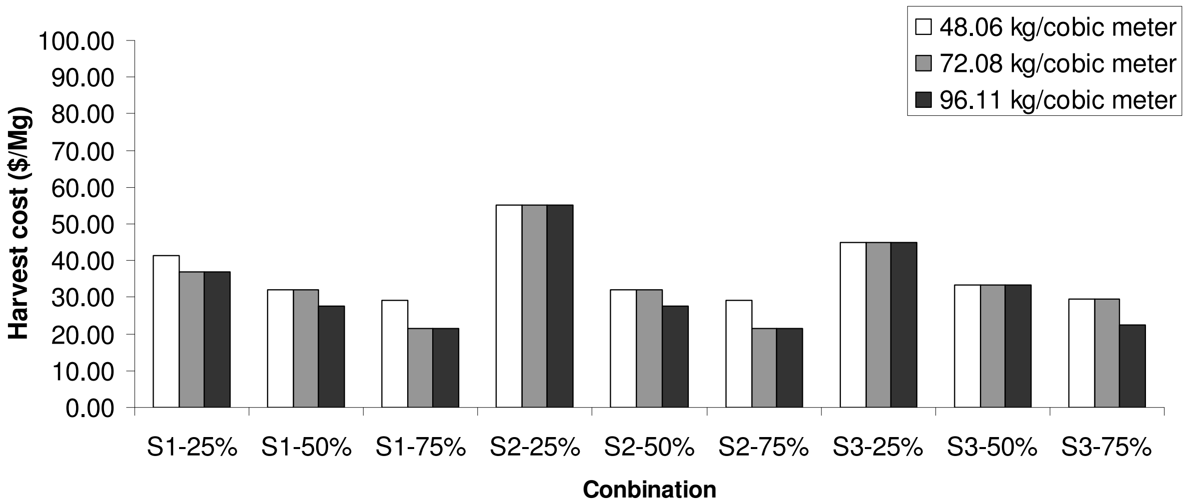

Figure 3. Effect from increasing density at 12.56 Mg/ha; per Mg cost was also decreased at higher density because of fewer equipment used

However, due to the nature of the systems, in practical it was not possible to collect fewer amount of stover in scenario 1 and 3 when there still was unused capacity; it would automatically achieve a higher collection percentage. The maximum collection percentage that could be achieved with the same equipment at each density was listed in table 6.

Table 6. Collection limit at each stover density at yield of 9.41 Mg/ha

Scenario	Equipment used*	Collection limit at each density		
		48.06 kg/m^3	72.08 kg/m^3	96.11 kg/m^3
Scenario 1 (Separated systems /Spillage)	1 stover tender (with 1 carts)	25%	33%	39%
Scenario 3 (Combined system /Spillage)	2 combined tender; grain cart used percentage of 30%	37%	55%	73%

* The same amount as required in previous evaluation at 25% collection level

B. Costs Relates to Stover Harvest

Nutrient replacement and storage cost played important roles compared with harvest cost.

Nutrient replacement cost

This cost depended on stover nutrient content, and thus for each unit mass, replacement cost was a constant. Including fertilizer prices, the nutrient replacement cost for the stover was \$14.5/ dry Mg. Per hactare cost varied with different collection levels and yields.

Storage cost

Two alternatives of storage were applied. The storage cost was affected by storage methods, equipment used, and total stover mass. The lowest cost was \$27.27/dry Mg at 9.41 Mg/ha and \$25.2/dry Mg at 12.56 Mg/ha. Costs from different combination are listed in Table 7 and Table 8.

Table 7. Storage cost (\$/ dry Mg) at different collection levels at 9.41 Mg/ha

	Stover collection level		
Storage method	25%	50%	75%
Covered piles	39.97	27.60	23.47
Plastic bags	43.90	31.43	27.27

Table 8. Storage cost (\$/ dry Mg) at different collection levels at 12.56 Mg/ha

	Stover collection level		
Storage method	25%	50%	75%
Covered piles	33.18	24.35	21.41
Plastic bags	37.67	28.31	25.20

Since the cover pile method has lower cost, it was chosen when calculating total cost.

C. Total cost

Total cost, including harvest, storage, and nutrient replacement at 9.41 Mg/ha was between \$76.67/Mg and \$132.44/Mg, depending on harvest logic, amount of stover collected, stover density, and storage methods. At the grain yield of 12.56 Mg/ha, total cost was between \$78.42/dry Mg and \$116.20/dry Mg.

On a per unit mass basis, harvest cost was 33% to 49% of total cost, which meant, the related costs should also be considered, especially when harvesting stover on a large scale.

The detailed total costs from different combinations are presented in Tables 9 and 10 below.

Table 9. Total cost, with covered piles storage method, at 9.41 Mg/ha

Scenario	Collection %	Cost of stover($/Mg)	Nutrient cost ($/Mg)	Storage cost ($/Mg)	Total cost ($/Mg)
Scenario 1	25%	42.06	14.5	39.97	96.53
	50%	32.29	14.5	27.60	74.39
	75%	25.30	14.5	23.47	63.27
Scenario 2	25%	64.57	14.5	39.97	119.04
	50%	37.95	14.5	27.60	80.05
	75%	25.30	14.5	23.47	63.27
Scenario 3	25%	52.09	14.5	39.97	106.56
	50%	39.49	14.5	27.60	81.59
	75%	26.32	14.5	23.47	64.29

Table 10. Total cost, with covered piles storage method, at 12.56 Mg/ha

Scenario	Collection %	Cost of stover($/Mg)	Nutrient cost ($/Mg)	Storage cost ($/Mg)	Total cost ($/Mg)
Scenario 1	25%	41.31	14.5	41.32	97.13
	50%	32.17	14.5	32.16	78.83
	75%	29.11	14.5	29.11	72.72
Scenario 2	25%	55.12	14.5	55.12	124.74
	50%	32.17	14.5	32.16	78.83
	75%	29.11	14.5	29.11	72.72
Scenario 3	25%	44.78	14.5	44.87	104.15
	50%	33.37	14.5	33.42	81.29
	75%	29.57	14.5	29.60	73.67

Conclusion

The harvest work could be done at a reasonable cost. The cost from single-pass harvesting was between $25.30/Mg and $64.57/Mg at yield of 9.41 Mg/ha, depending on the equipment use related to collection level. Yield, combine speed and on-board capacity had effects on the cost, and the on-board density was an important factor in the cost. Further advancement on equipment in order to better utilize the equipment would be required to reduce harvest costs to make the harvest work more competitive.

Storage cost and nutrient replacement was as important as the harvesting cost in some situations. The total cost including harvest, storage, and nutrient replacement is likely to be between \$63.27/Mg and \$119.04/Mg at 9.41 Mg/ha.

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CHAPTER 3

Cost Analysis of Single-pass Corn Cob Harvest Systems

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Abstract

Three corn cob harvest systems were evaluated in order to estimate the impact from cob harvesting on typical grain harvest work. The three single-pass harvest methods evaluated were corn-cob mix (CCM), with cob caddy, and with a dual-stream harvest system. All systems increased harvest working time by 8% to 25%, as well as increasing in-field traffic and labor requirements. The dual-stream system had the least impact on grain harvest and had the lowest cost. With nutrient replacement and long-term storage, the overall cost of the three scenarios at a grain yield of 9.41 Mg/ha were \$73/Mg, \$101/Mg and \$55/Mg for CCM, Cob Caddy and dual-stream systems, respectively.

Introduction

Facing the energy shortage in the coming generation, biofuels have been emphasized as one important area for meeting increasing energy demand. Ethanol is a relatively attractive alternative fuel, with its ability to be blended with and to replace gasoline (Young et. al., 2007). To provide a sustainable basis, cellulosic ethanol is preferred due to its lower life

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[1] Corresponding author; designed study; reviewed model; reviewed and edited paper
[2] Provided equipment performance data; reviewed and commented on paper.

cycle net energy requirement and reduced carbon dioxide emission (Farrell et. al, 2006). Agricultural residues, with steady annual yields, are serving as a second generation cellulosic ethanol feedstock (BRDB, 2008).

Since corn is produced as a main crop, corn residues are a huge resource providing cellulosic biomass (Perlack et. al., 2005). However, environmental concerns related to soil erosion and nutrient loss problem accompany corn residue harvesting. A study suggests that removing 25% or less of corn residues will ensure land sustainability (Blanco-Canqui, et. al., 2007). Thus, removing only the cob portion has become another industrial alternative.

Economic aspect on harvesting is important in ethanol production, with the cost of feedstock playing a major part in ethanol production costs. There are analyses and studies describing cost of corn grain and starch ethanol production based on previous cob collection (ISU Extension, 2008, McAloon et. al., 2000). In the past, cobs were collected with harvesting methods such as corn-cob-mix harvesting and applying cob caddies (Davidson, 2008). Beyond traditional methods, an advanced single-pass harvest system, having the ability to collect cobs with independent biomass streams during normal grain harvesting, was developed.

Based on previous studies and surveys, the objective of this study is to establish a model based on representative corn farm information in Iowa, with available cob-harvesting methods applied, and then to estimate the cost, time, and labor demand within cob harvest systems, in order to estimate the effect and profit from existing and advanced cob collection technologies.

Material and Methods

Evaluation was conducted in three parts; cob harvesting and transport costs, storage costs, and nutrient replacement costs.

A. The harvest and transport model

The harvest and transport model determines costs under certain assumptions. It includes three main sections: (a) Combine harvesting section, (b) in-field transportation section, and (c) harvest budget section.

Combine harvesting section

In this section, the combine harvesting rate and material flow rate was determined for average field yield with additional delays possible due to harvesting the additional biomass (cobs). Delay was also possible if there was not enough grain hauling equipment, so that the combine would be slowed down waiting for the next returning hauler.

Three cob harvesting scenarios were evaluated in conjunction with combine grain harvest for this study:

(a) Corn Cob Mix (CCM) scenario

A modified combine, with the capability to harvest grain and cobs at the same time, was applied. Grain and cobs were mixed in the material stream, and were stored in the combine bin or in hauling carts together. The combine itself is running continuously at an average speed. Mixed grain and cobs required further separation at the edge of the field.

(b) Cob Caddy scenario

A combine without modification was used in this scenario with a cob caddy pulled after the combine. Grain was stored in the bin as usual; other materials coming out the combine were collected and separated at the cob caddy side, with only the cob portion collected in the caddy. When the caddy was full, the whole system stopped and dumped cobs into hauling carts.

(c) Dual-stream scenario

A modified combine with the ability to chop and separate the cob portion was applied. Two material streams, one grain stream and one cob stream, come out of the combine and area stored in separated carts. The combine itself is running continuously at an average speed.

In-field transportation section

Materials from the combine were hauled to the edge of the field and temporarily stored. Hauling work was done with tenders. The tenders referred to one of the three following designs: (a) A tractor pulling a grain cart (grain tenders), (b) a tractor pulling a cob cart (cob tenders), or (c) a tractor pulling a grain cart and a cob cart (combined tenders).

Those tenders were running at a constant speed in the field. The hauling distance was also assumed constant. In the CCM and the cob caddy scenarios there was no cob loss; in the dual-stream scenario, while the combined tender left the combine there was no temporary storage for cobs and cobs were dumped on the ground.

The speed of tenders was constant, so in order to accommodate the continuous material flow, more tenders were required with a higher flow. The number of tenders was determined by the model in order to maximize net revenue from grain and cob harvesting. Grain was not allowed to be lost during harvesting, and thus the combine speed was limited in some cases with fewer available tenders to maintain a lower cost.

Separation section

Only the CCM scenario had this section. Mixed grain and cobs were temporarily stored in a tank, and then continuously separated at a constant rate by an on-site separator.

Harvest budget section

The harvest cost included both capital costs and operation costs, and were mainly related to annual operation times. Costs were calculated from formulas from Iowa State University Extension Document PM710 and ASABE standard document EP496.

The only important change was in fuel consumption. Additional power was required due to the extra material processed in the combine. The extra power required in the dual-stream system with biomass harvesting was calculated from the following formula derived from experiment results:

Extra power requirement (kw)=

*(1.65 * Biomass feeding rate (Mg/hr) +17.13)*

Thus, the fuel cost was derived from (original + power requirement).

In this model, the aim of optimization was to minimize the whole harvesting cost, with all cobs collected. The definition of cob harvesting cost was the cost differences between harvest scenarios with cobs and without cobs (grain-only). After the cost was obtained, both grain and cobs were assigned a price, and the net revenue reflected the whole harvest cost subtracted from the income from both grain and cobs.

All assumptions used in the model are presented in Table 1 and Table 2.

B. Nutrient replacement cost

In order to replace nutrient removed with the cobs, additional fertilizer application at the next farming period is assumed to be necessary. The replacement cost is the sum of N, P, K fertilizer prices. It is not included in the former harvest cost.

The detailed costs are listed in Table 3.

C. Storage cost

The cost to store cobs at the edge of field was evaluated. It was assumed the cobs were left in piles at the edge, and the cost was from labor work, dry matter loss, and pad material (if applied). Storage criteria are presented in Table 4. The DM loss percentage was from previous studies (Smith et al., 1985) over an 18-month storage period.

Table 1. Common Harvesting Constants

Category	Item	Value
Combine	List Price ($)	200,000
	Power (kW)	242.35 (325 HP)
	Bin Capacity (m^3)	10.6
	Bin Unloading Rate (m^3/min)	5.5
	Theoretical Field Speed (m/min)	101.9

Table 1 (continued). Common harvesting constants

Category	Item	Value
Corn head	List price ($)	30,000
	Head Width (m)	9.1
Tractor & Trailer Set	List price - Tractor ($)	75,000
	List price - Trailer ($)	27,000
	Power (kW)	78.3 (105 HP)
	Field Speed (m/min)	268.2
	Trailer Capacity (m^3)	30.3
	In field hauling distance (m)	1609
Cob Caddy	List price ($)	90,000
	Power (kW)	74.56 (100 HP)
	Capacity (m^3)	25.9
	Unloading time (min)	1
Field	Area (ha)	809.37 (2000 acre)
	Evaluation unit (ha)	64.74 (160 acre)
Economics	Real Interest Rate (%)	8
	Wage Rate ($/hr)	15
	Hired Labor (%)	100
	Diesel Price ($/liter)	1.06 ($4/gal)
Biomass	Cob Volume Ratio (to grain)	1.0
	Cob bulk density (kg/m^3)	248.29
	Grain Price ($/Mg)	196.8
	Cob DM ratio to dry grain[3]	0.18

[3] Shinner et al., 2007.

Table 2. Variables in each scenario

Category	Item	CCM	Cob Caddy	Dual Stream
Combine	Modification Cost ($)[4]	23,000	0	35,000
	Field Efficiency[5]	73%[6]	73%[7]	73%[8]
	Speed Reduction Factor*	85%	80%	92%

* Speed reduction due to cob harvesting

Table 3. Nutrient contents in cobs (Iowa State University Extension)

Category	% of cob dry mass	Price ($/kg)
N	0.42%	1.10
P	0.08%	1.76
K	0.76%	0.88

Table 4. Storage criteria

Category	Item	Value
Pile	Diameter[9]	45.1 m
	Height	18.3 m
	Density	248.29 kg/m^3
	Filling rate	17.6 m^3/min
	Padding cost	5.38 \$/m^2
	Average DM loss	13%
Labor	Wage	15.0 $/hr

Results and Discussion

A. Representative cob-harvesting cost

Using a set of typical assumptions, cost was first evaluated to present only the general idea of harvest cost. Three designs were evaluated in this model. In order to compare three scenarios fairly, in all scenarios it was assumed that 100% of cobs were collected.

[4] S. Birrell, previous research result
[5] S. Birrell, previous research result
[6] ISU Extension documents A3-24
[7] ISU Extension documents A3-24
[8] ISU Extension documents A3-24
[9] The relationship between size and DM loss was from Smith et al., 1985 and Kenney et al, 2009

Harvesting cobs resulted in two main impacts: longer harvest times and increased field traffic. Since cob collection reduces the average combine speed by processing extra biomass or pulling additional equipment, the harvest time length was increased by 8 to 25%.

Additionally, temporary storage space was required for cobs, although the density of cobs was high and necessary space was therefore minimal. In all three cases, one additional tender was required, inducing extra traffic and labor requirement during harvest time.

Furthermore, the Cob Caddy scenario required more capital investment and operation cost (the cob caddy) and the CCM scenario required additional work to separate grain and cobs. These costs were also reflected in the unit cost. Based on the design, the dual-stream scenario required the least additional work. It also had the lowest possible cost for cobs at $33.17/Mg at 9.41 Mg/ha. Harvest work summaries are presented in Table 5 below.

B. Harvest work on different yields

Following the typical cost evaluation, results on different yield were obtained. At each yield, the same evaluation was done to minimize the harvest cost. Results for different yields were compared among the scenarios.

Table 5. Results from three scenarios

Scenario	Yield (Mg/ha)	Number of tenders	Total labor hours	Harvest time length (hr)	Harvest cost ($/ha)	Harvest cost ($/dry Mg)
CCM	9.41	2	9834	245	74.85	50.51
	13.18	2	1164	291	94.07	45.27
Cob Caddy	9.41	2 (1+1)*	784	261	114.61	78.45
	13.18	2 (1+1)	927	309	140.13	68.40
Dual Stream	9.41	2	678	226	47.91	33.17
	13.18	2	802	267	55.06	27.12
Grain only	9.41	1	418	209		
	13.18	1	495	263		

*The amount of tenders in Cob Caddy's case, which showed as "2 (1+1)", represents 1 grain tender and one cob tender, 2 in total.

Cost Variation with Yield

Figure 1 below presents the cob harvesting cost for different yields. Except for the CCM scenario, the per hectare costs rose smoothly with the yield. This resulted mainly from increased harvest time. The increase in the interval 5.65-8.16 Mg/ha on the CCM curve indicated the point when harvest reached the point that adding another tender resulted in shorter harvest time and lower overall cost, or, alternatively, the harvest time would be delayed significantly. At lower yield values, one tender was enough for the mixed biomass stream.

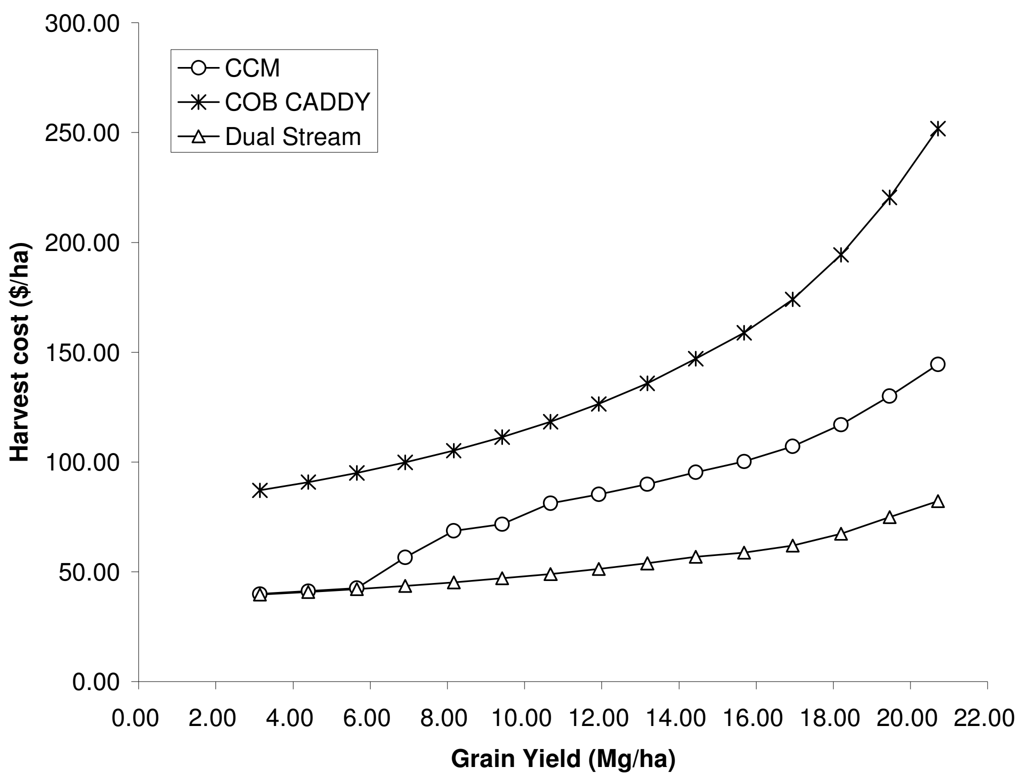

Figure 1. Per hectare cost rose with the yield due to increased harvest time and accumulated labor hours.

Figure 2 below is based on the same results but on per Mg basis. Average cost was higher at low yield, when the harvest work was done with the same amount of equipment but obtaining fewer cobs per hectare.

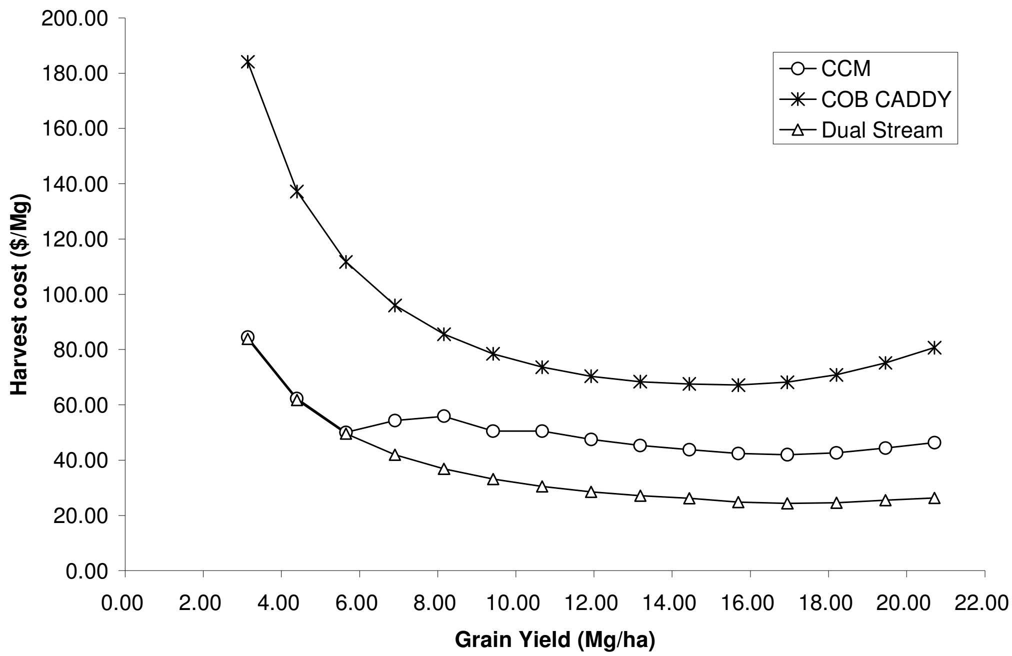

Figure 2. Per Mg cost for cobs for different yield; cost was decreased as more material are harvested, except at the high yield end, cost rose due to significantly increased harvest time.

Labor requirement on yields

There were labor requirement more then typical grain harvesting due to applying more equipment while harvesting. Figure 3 presented the additional amount of labor required in each cob harvesting scenario during harvesting, and figure 4 describes the additional labor-hour requirement in each scenario. It was the accumulated hours that included all labor needs in different harvest tasks, and thus was a multiplier of the actual harvesting time in each scenario.

The grain-only scenario used one grain tender at all times; the dual-stream and the cob caddy scenario required additional one tender for cob harvesting at all yields; the CCM scenario required an additional tender after grain yield came to 8.16 Mg/ha, and at the same time additional labor was also necessary for separation, thus the overall labor hour is higher.

Among the three cob-harvesting scenarios, the dual-stream scenario required the fewest additional labor hours, since the system was similar to the grain-only harvest scenario. The difference between dual-stream and grain harvest scenario was due to lower harvest efficiency when also harvesting cobs, and the extra tender required in order to collect 100% cobs.

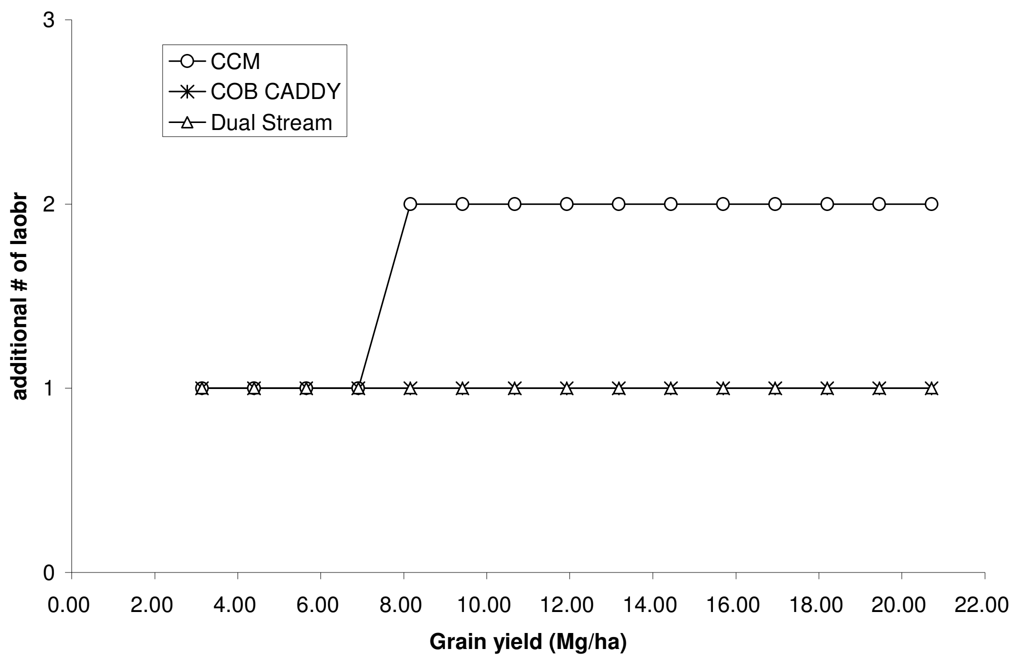

Figure 3. Additional number of labor required during harvest over yields; the CCM scenario require more labor for separation work

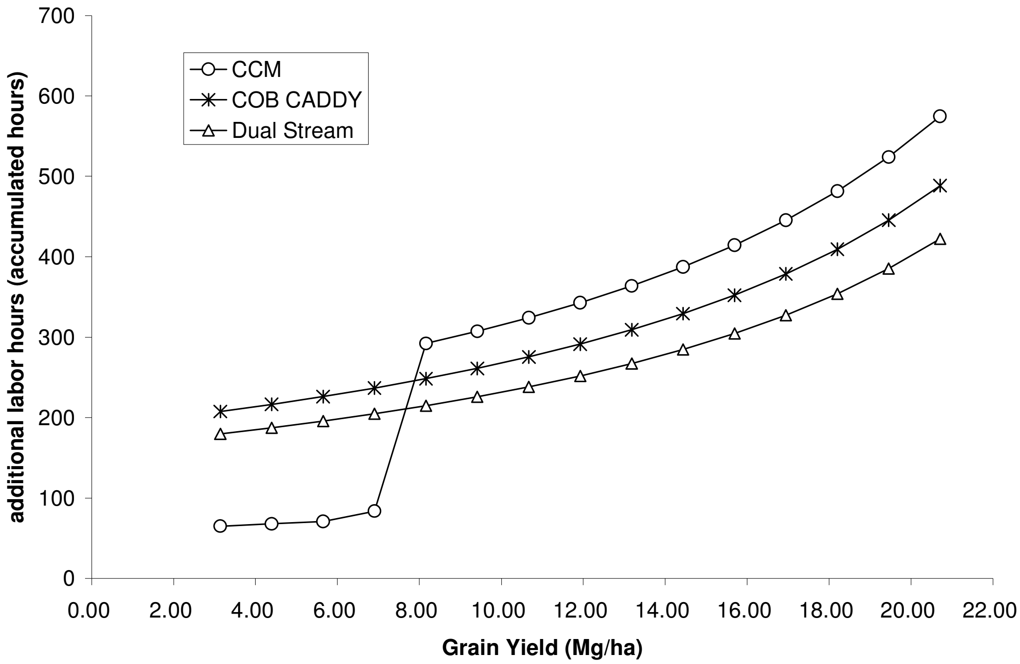

Figure 4. Additional labor hours on different yield; the CCM scenario requires separation thus is had the highest accumulated labor hour

C. Nutrient replacement cost

Applying the cob nutrient content and recent prices of fertilizers, the nutrient replacement cost was \$12.74/dry Mg cob. It might be nearly the same as harvest cost in some conditions.

D. Storage cost

Using the assumptions in Table 4, the storage cost was estimated to be \$10.02/Dry Mg with pad or \$4.64/Dry Mg without pad.

E. Total Cost

With the nutrient replacement cost and storage cost included, the total costs are presented in Tables and 7 below. It came to about $73/dry Mg for CCM, $101/dry Mg for Cob Caddy, and $56/dry Mg for Dual stream, at the grain yield of 9.41 Mg/ha.

Table 6. Results from three scenarios (Storage on pads)

Scenario	Yield (Mg/ha)	Cost of Cobs ($/dry Mg)	Nutrient replacement cost ($/dry Mg)	Storage Cost ($/dry Mg)	Total Cost ($/dry Mg)
CCM	9.41	50.51	12.74	10.02	73.27
	13.18	45.27	12.74	10.02	68.03
Cob Caddy	9.41	78.45	12.74	10.02	101.21
	13.18	68.40	12.74	10.02	91.16
Dual Stream	9.41	33.17	12.74	10.02	55.93
	13.18	27.12	12.74	10.02	49.88

Table 7. Results from three scenarios (Storage without pad)

Scenario	Yield (Mg/ha)	Cost of Cobs ($/dry Mg)	Nutrient replacement cost ($/dry Mg)	Storage Cost ($/dry Mg)	Total Cost ($/dry Mg)
CCM	9.41	50.51	12.74	4.64	67.89
	13.18	45.27	12.74	4.64	62.65
Cob Caddy	9.41	78.45	12.74	4.64	95.83
	13.18	68.40	12.74	4.64	85.78
Dual Stream	9.41	33.17	12.74	4.64	50.55
	13.18	27.12	12.74	4.64	44.50

The total costs over all yields were presented in the figure 5 below. Generally, average cost was lower when more material was harvested; however, the increased harvest time resulted in higher average cost at high yield end.

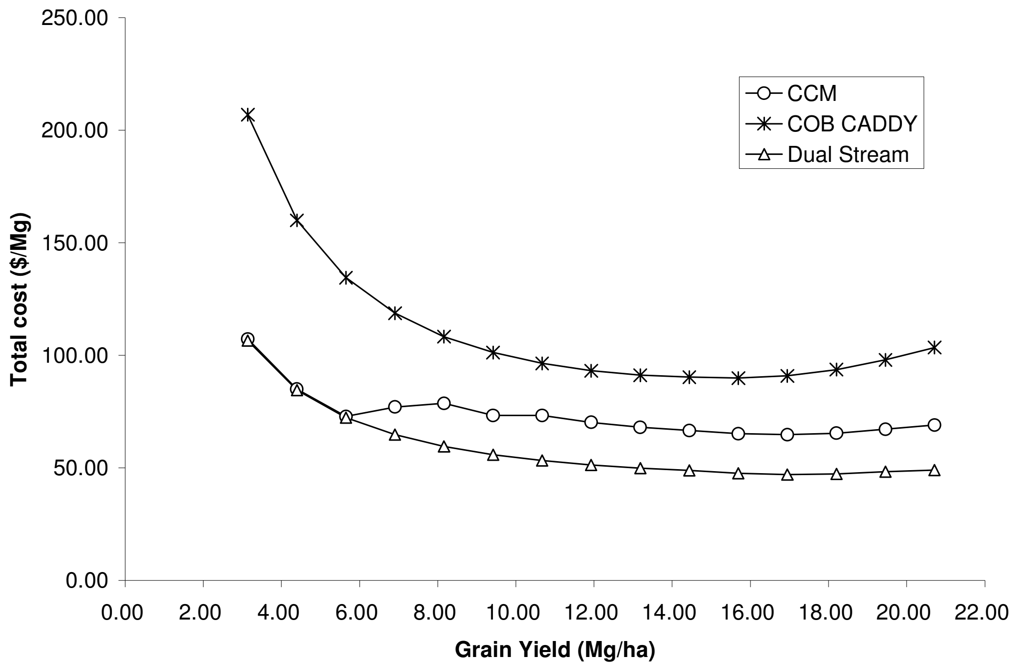

Figure 5. Total cost including storage and nutrient replacement vs. yield; the per Mg cost was higher at the high yield end due to increased harvesting time

Conclusion

Although harvesting corn cobs requires additional labor, machinery and longer harvesting time, it could still bring profit to farmers, depending on the price of cobs. For three scenarios across representative yields, the harvest cost itself for cobs ranged from $33/dry Mg to $51/dry Mg. The least cost cob-harvesting scenario on all yields was the dual-stream scenario with its lower labor and equipment requirements. Nutrient replacement and storage also resulted in costs that may not be neglected. The total cost, including nutrient replacement and storage, came to between $56/Mg and $101/Mg.

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CHAPTER 4

General Conclusion

Corn residue harvest systems, including both stover and cobs, were evaluated for their impact on traditional grain harvest operations. In the evaluation, time is the main variable leading to differences in labor and equipment requirements and costs.

The time required for harvest of grain and stover is larger than for grain alone because the harvester is slowed down due to power limitations and because of more complex in-field logistics involving many more pieces of equipment. The harvest time is about 10% to 25% longer than for the grain-only case, depending on the method chosen.

The single-pass equipment analyzed for stover harvesting induced extra traffic and labor requirements in the field. Depending on the material flow rate, one to three tenders were required to support the combine, significantly increasing the total labor needed during harvesting, as well as in-field traffic. The residue material flow rate was determined by on-board storage density; in the single-pass stover systems, increasing density to 96 kg/m^3 was sufficient to reduce the additional hauling equipment need to one unit. For the cobs, since their bulk density is higher and yield is lower, hauling capacity is not as important as in the stover systems.

The cost of stover harvesting, assuming all equipment is used only with corn harvesting, is between about $25/Mg and $65/Mg when the grain yield is 9.4 Mg/ha. The cost difference is due to amount of target residue collection and choice of equipment movement logistics. When collecting larger portion of the residue, the collection cost can be similar to that of traditional custom work, but it has the advantage of being done within the grain harvesting period, and reducing the field drying time required by traditional harvesting methods, and is therefore more convenient as a long-term feedstock supplement. If only collecting the cob portion, then the harvest cost is about \$33/Mg to \$50/Mg. Although the per hectare costs of stover harvesting is higher than cobs, the significant difference between stover yield and cob yield leads to the result that per Mg cost is similar.

As mentioned above, the on-board density is an important issue with respect to the hauling system. In the evaluation, methods with higher stover density (either the assumed high-density cases) had lower cost (the later is around \$19/Mg to \$56/Mg when grain yield is 9.4Mg/ha), and in some cases shorter stover-collection time (lower then 50% of grain harvesting time).

Following the harvest cost, nutrient removal and storage are also important costs that must be considered. If nutrients removed with the biomass are going to be reapplied, the storage and nutrient replacement cost combined can be 30% to 50% higher then the harvest cost itself. When compared to the collection cost, the costs of nutrient replacement and storage are significant.

To conclude, the biomass harvest work will have a range on impacts that should be considered but have not been quantified in this analysis. The first issue is timeliness. Harvest of residue will slow down the grain harvest. Depending on the field area and actual yield, the increased harvest time could be significant; for example, in the stover harvesting scenarios, when the grain yield was 12.56 Mg/ha in an about 800 ha field, slowing down by 25% could mean about 60 additional hours to finish the harvest work.

At the same time, additional labor would be required during the whole harvest time, not to mention higher requirement with other additional tasks. It would need at least 1, but could be up to 3 more people in the field in some stover harvest scenarios. This raises the concern as to whether this labor requirement can be met during the harvest season. The added labor also changes the harvest routine when now several additional laborers are required to be working in the field at the same time. It would also be different to the traditional custom work which is done after grain harvesting period.

Grain quality would change during the lengthened harvest period, also the risk of weather delay and damage are increased. Since the harvest window is generally less then 80 days (Hettenhaus, 2000), and the optimum harvest window is ever shorter, if the harvest work could not been done simultaneously due to labor limitation, any delay would play an important role in harvest work.

In addition, heavier traffic in the field represents possible higher soil compaction, which reduces soil productivity. On-board stover densification helped to reduce equipment usage and thus lessen the concern; but the method to densify the material requires more study, along with the difficulty to further densify corn cobs. Removing covering stalks from the field surface would also induce change to the field; although the answer to whether removing stover material from the field leads to negative effects is different from site to site, studies suggest that only removing a small fraction of stover, for example less than 25% (Wilhelm et al., 2007; Blanco-Canqui et. al., 2007), would help maintain soil productivity. From this aspect, only removing the corn cob portion seems to be a better alternative; however, the lower per-hectare yield make cobs unfavorable: At the grain yield of 9.41Mg/ha, the dry cob yield is about 1.4 Mg/ha, which means even if the cob price is high enough to earn $50 per Mg, the income from cobs is still as low as $70/ha, while the income from grain would be about $1900/ha with the typical price of about $197/Mg ($5/bu) for grain; the income from stover may be three to four times that from cobs depending on the amount collected. Lower cob density also raises the concern that in order to fulfill the same feedstock requirement, the collection area would be at least 2.8 times larger for cobs then for stover, and it would induce differences either in transportation in or outside the field, or in the overall availability of feedstock supply.

Furthermore, this evaluation was working on optimal estimation; the dynamics in actual harvest work was not able to be estimated in the project. As it mentioned above, lengthened harvest time might cause issues such as losses due to weather; increased labor requirement might lead to further harvest delay when organize equipment in the field as assumed in the optimal scenario. There were also some possible sources of cost that were not included in this study, such as transportation outside the field, which is expected to be a significant cost. The actual cost of corn stover and cobs are likely to be higher than estimated here.

Future work

This study was based on a model with general parameters and thus may not present detailed differences from site to site. For fields with special characteristics, computer simulation may be required to track real-time equipment movement and need.

The harvest method was also limited; there were only one kind of single-pass stover harvest system evaluated. A brief summery of another possible system, which is the single-pass baling system, was provided as appendix B; however, other harvest systems, as well as storage methods unlisted in this study, might worth evaluation when cooperating with specific case requirement. The on-board densification system was also not yet practical to be able to evaluate, and may be studied in future research.

Changes besides cost from the additional harvest work are also requiring evaluation; for example, if the labor requirement could be fulfilled or not, and the environmental effects to the field from additional harvest task requires studying based on specific field condition.

In addition to field work, the life-cycle energy for residue harvesting is also an important topic when evaluating the feasibility of residue feedstock, and may be examined in future studies.

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Appendix A

Model logic description

Detailed model design logic is presented in this section.

1. Combine harvesting section

This section worked with field capacity and material flow.

Field Capacity

$$CFC = Head\ width \times Field\ efficiency \times Field\ speed \times Reduction\ factor \times L$$

• Head width was the corn head width in meter

• Field efficiency was the estimate of harvest efficiency, in decimal

• Field speed was the theoretical combine speed in m/min, derived from a yield-based formula

• Reduction factor was the speed reduction due to extra material entering the combine, machine modification and slowed by equipment pulled behind the combine. This factor was different in each scenario.

• L is the delay factor, which depended on hauling condition; the calculation is in a later section.

In order to simplify equations later, the term CFC_0 was defined as:

$CFC_0 = Head\ width \times Field\ Efficiency \times Field\ Speed \times\ Reduction\ factor.$

Thus, the formula could be simplified as:

$CFC = CFC_0 \times L$

Material flow rate

The grain harvest rate directly depended on the combine field capacity.

$KHR = Grain\ Harvesting\ Rate\ (m^3/min) = CFC \times Yield$

• Yield was converted into bulk volume (m^3).

The definition of one bushel used in the model was 56 lb at 15.5% MC of grains, and the volume is $0.0303m^3$.

Then, the residue material (stover or cobs) harvest rate was:

$MHR = Material\ Harvesting\ Rate\ (m^3/min) = KHR \times CV$

• CV is the proportion of volume of residue material to 1 unit volume of kernel. For cobs, it was a constant; for stover, it would be changed by on-board storage density.

2. In-field transportation section

This section evaluated the usage of hauling equipment and their working condition during harvesting work.

Travel time

The first item was the tractor traveling time from the combine to the edge of the field and then back to the combine:

$Ttravel_0\ (min) = Traveldistance/Speed_{tractor} + Tunload$

• The notation 0 indicated that the traveling time was the basic situation when there was only one grain tender.

• Traveldistance was a constant, and the value depended on different estimation methods presented in a following section.

• T_{unload} was the time required for unloading (min), defined as (cart capacity)/(unloading rate).

• $Speed_{tractor}$ was the speed of tractor (m/min), also a constant.

Then, average tender traveling time (Ttravel) was defined as

$Ttravel\ (min) = Ttravel0\ /\ number\ of\ tenders.$

It was a function of the quantity of equipment.

Material filling time

Those filling time below were estimated to evaluate equipment working condition.

(a) Combine bin filling time: *Bin capacity / Material flow rate*

a. In the CCM model, the material flow rate was (KHR+MHR)

b. In other models, the material flow rate was KHR.

(b) Grain cart filling time: *Cart capacity / Grain bin unloading rate*

(c) Residue material cart filling time: *Cart capacity / MHR*

a. In the Cob Caddy model, this item was replaced by the following two:

i. Cob Caddy filling time: *Cob Caddy capacity / MHR*

ii. Material cart filling time: *Cart capacity / Unloading rate*

Delay factor L

The combine speed was actually limited by grain hauling condition. In the model, no grain was allowed to be lost; thus, if the combine bin would be full before an empty grain cart could catch on, it would either running at a constant slower speed, or more grain hauling equipment would be applied. Which alternative was applied was determined by cost; the highest profit alternative was chosen.

In this model, the traveling time is calculated based on a 64.74 hactare field unit. Thus, the value of L would be:

L=1 when traveling time is less than bin filling up time

$L = \frac{TBfull_0}{Ttravel}$ when traveling time is larger than bin filling-up time

Material loss

This was a section in stover harvesting scenarios and the single-pass dual-stream cob harvest system. During stover harvesting, since there were no storing space for stover on the combine, material would be lost between two stover tender runs, or during grain-filling procedure in some designs.

The basic-case loss percentage was defined as:

Loss percentage = (filling time) / (filling time + time between two runs).

For the stover harvest system working with combined tenders (which means a tractor pulling a grain cart and a residue-biomass cart), at the time period when the biomass cart was full but the grain cart was still being filled, residue biomass would be lost. It was defined as time gap. Thus, the loss percentage was defined as:

Loss percentage = (filling time) / (filling time + time between runs + time gap).

3. Budget-related section

After estimate machine use on the farm, costs and labor need could be estimated.

Available biomass

The mass of gathered residue biomass was:

Harvested biomass (kg)

= Yield in volume × CV × AREA × bulk density × harvest percentage

×(1-Loss percentage)

Total harvesting time

The grain harvesting time was estimated by the following formula:

$$\textbf{\textit{WHR}}\ (hr) = \frac{160acre}{CFC \times 60} \times \frac{AREA(acre)}{160acre}$$

• WHR is the total working time.

• CFC is already alternated by biomass hauling condition.

Then, the working time for each tender was the same as the combine working time, except for single-pass baling cases.

This harvesting time was used in farm-economic-related formulas as the annual working time.

Appendix B

Evaluation of Single-Pass Baling Harvest System

Introduction

Following the previous single-pass harvest system design, another single-pass collection alternative was proposed. The single-pass baler system integrated combine harvesting with a baler that was pulled behind the combine and directly baled all materials from the combine. Stover bales were left in the field waiting to be hauled later to the edge of the field. A spreadsheet model similar to the previous single-pass system evaluation model was built in order to evaluate the changes this new system had on harvesting work.

The single-pass baling model is described below in three sections: combine harvester, bale transportation, and budget.

Combine Harvester Working Section

The combine harvester system included a modified combine pulling a large square baler. For this model, combine speed was estimated by the yield with the speed reduction due to pulling the baler. The combine speed remained constant throughout harvest work. The speed was estimated from a function derived from experimental results:

Theoretical combine speed (m/min) = (-0.01 × yield in bushels + 5.37) × 26.82

Actual combine speed (m/min)= Theoretical combine speed × speed reduction

The material flow rate depended on the actual combine harvest speed and harvest index. All stover leaving the combine directly entered the baler and was baled during harvesting work. Bales were left in the lanes. The combine simultaneously baled and harvested grain, with the cooperation of grain tenders.

Bale Transportation Section

Bales were transported to the edge of the field using one of two hauling systems: a Stinger Stacker, or a tractor with bale spears.

With the Stinger Stacker method, all bales were moved to the edge of the field and stacked. The transporting rate was estimated with the machine's average performance information .

The tractor with bale spears method involved moving all bales to the edge of the field. The transporting rate depended on tractor capacity, the number of bales per lane, and the tractor speed which was constant during collection work. The average transportation distance depended on the average number of bales per lane. The assumed bale characteristics are listed in table 1 below.

Table 1. Bale Characteristics

Item	Value
Size	0.91 m × 1.22 m × 2.44 m (3 ft × 4 ft × 8 ft)
Moisture content	40%
Dry density	224 kg/m^3[1]

Budget Section

Changes to the harvest work, including labor needs, equipment requirements and harvest time, were estimated. The final cost, including both operational and capital costs, was basically a function of time. Detailed costs were calculated from formulas obtained from Iowa State Extension Document PM710 and ASABE standard document EP496.

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1 From Sokhansanj& Turhollow 2002, pp. 525-530. 525–530.

Fuel consumption was the major change in this model. It was assumed that additional horsepower (HP) was consumed during stalk processing and was a function of biomass feeding rate based on prior experimental records.

*ExtraPower (kw) = (1.65 * Biomass feeding rate (Mg/hr) +17.13).*

Thus the power value used to obtain the fuel cost became (original HP + Extra HP).

The main assumptions in the model are listed in Table 2 below.

Table 2. Model Assumptions

Category	Item	Value
Combine	List price ($)	200,000
	Power (kW)	242.35 (325 HP)
	Bin capacity (m^3)	10.6
	Bin unloading rate (m^3/min)	5.5
Baler	List price ($)	61,100
	Power (kW)	29.83 (40 HP)
	Speed reduction to the combine	10%
Corn head	List price ($)	30,000
	Head Width (m)	9.1
Tractor	List price - Tractor ($)	75,000
	Power (kW)	78.3 (105 HP)
	Field Speed (m/min)	268.2
Grain carts	List price - Cart ($)	27,000
	Capacity (m^3)	30.3
Tractor for bale spear	List price ($)	37000
	Power (kW)	55.93 (75 HP)
Bale spear set	List price ($)	620[2]
	Capacity	2 bales
Stinger Stacker	List price ($)	184000[3]

[2] From Stinger inc. homepage (http://www.stingerltd.com/products/spears/spears.htm)
[3] From Stinger INC. official information, obtained from personal communication. [Same points as above.]

Table 2 (continued). Model Assumptions

Category	Item	Value
	Power (kW)	227.43 (305 HP)
	Capacity (m^3)	12 bales
	Average transporting rate	60 bales/hr, within one field unit
Field	Area (ha)	809.37 (2000 acre)
	Evaluation unit (ha)	64.74 (160 acre)
Economics	Real Interest Rate (%)	8
	Wage Rate ($/hr)	15
	Hired Labor (%)	100
	Diesel Price ($/liter)	1.06 ($4/gal)
Biomass	Harvest Index	0.52
	Stover bulk density (kg/m^3)	48.06
	Grain Price ($/Mg)	196.8
	Stover Price ($/dry Mg)	100

Summary of Results

Compared to other the single-pass collection designs, the costs associated with the single-pass baler were lower because this system required less collection equipment and a shorter collection time due to higher on-board density and no need to haul materials immediately after they leave the combine.

However, pulling a baler further decreased harvesting speed, and the harvest time was10% longer than previous stover harvest scenarios. Harvest costs of the single-pass baler were estimated to be between $19/Mg and $56/Mg with a Stinger Stacker and $17.05 to $52.45 with a tractor with bale spears, at 9.41 Mg/ha.

Table 3. Baling with Stinger Stacker

Yield	Collection %	Total labor hours	Harvest time (hr)	Stover collection time (hr)	Cost of stover($/Mg)
9.41 Mg/ha	80%[4]	668.8	288.4	92	18.60
	50%	634.8		58	28.91
	25%	605.8		29	56.41
12.55 Mg/ha	80%	785.4	331.2	123	16.12
	50%	739.4		77	24.95
	25%	700.4		38	48.50
15.69 Mg/ha	80%	931.8	388.9	154	15.12
	50%	873.8		96	23.35
	25%	825.8		48	45.28

Table 4. Baling with a tractor with bale spears

Yield	Collection %	Total labor hours	Harvest time (hr)	Stover collection time (hr)	Cost of stover($/Mg)
9.41 Mg/ha	80%	718.8	288.4	142	17.05
	50%	683.8		107	26.75
	25%	647.8		71	52.45
12.55 Mg/ha	80%	890.4	331.2	228	15.60
	50%	799.4		137	23.91
	25%	753.4		91	46.80
15.69 Mg/ha	80%	1035.8	388.9	258	15.04
	50%	932.8		155	23.11
	25%	880.8		103	45.29

[4] 80% is the default case which baling all material from the combine. For 50% and 25% cases, it was assumed that some stover was deposed on the field with some system modification.